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Multi-Resolution Processing (MRP) to Enhance Knowledge-Aided STAP

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Outline

- **MRP CONOPS**
- Long Dwell Processing
- Benefits
- Target Motion Effects
- Summary

Historical Evolution of SAR and GMTI

DBS

1-Channel, Short CPI

Image formation is more sophisticated than a simple FFT

SAR

1-Channel, Long CPI

DPCA

2-Channel, Short CPI

Space-time <u>deterministic</u> processing

Movers can be detected exo-clutter and by exploiting defocusing

Height measurement

IFSAR

2-Channel, Long CPI

ADPCA

2-Channel, Short CPI

Space-time <u>adaptive</u> processing

Along-track arrangement of channels can detect movers a al DPCA

A consequence of STAP architectures and multi-mode operation

MSAR

N-Channel, Long CPI

STAP

N-Channel, Short CPI

Fully-adaptive with several spatial DOFs

SAR & GMTI

N-Channel, Long CPI

Multi-Resolution Timeline

BASELINE MODE	MULTI-RESOLUTION MODE
Wide-Area Search (WAS)	Dwell on Area of Interest
Waveform Diversity	RF and PRF Fixed
Narrowband	Narrowband or Wideband
Uses *a priori* Knowledge	Knowledge De-Emphasized

A priori knowledge progressively de-emphasized as dwell time increases and resolution becomes finer

Short-Dwell GMTI	Short-Dwell GMTI	→	Short-Dwell GMTI	MoComp To Line	MoComp To Point	SAR Imaging (PFA)

0	75ms	150ms	0	0.07s	0.25s	0.5s	1-2 s
0	3x32-48	3x32-48	0	128	512	1024	2,000-4,000

- MRP mode initialized by WAS mode because an area of interest…
  - 1. Appears challenging (severe heterogeneity), based on *a priori* knowledge
  - 2. Is expected to contain slow movers (very low MDV is required)
  - 3. Has movers that need to be tracked through clutter (“cradle-to-grave”)

Multi-Resolution STAP

- Post-Doppler STAP is used under all circumstances
  - All adaptive processing is examined from the context of the Extended Factor Algorithm (EFA)
  - EFA is a convenient model for bridging the gap between traditional GMTI STAP and GMTI SAR image processing
- EFA Advantages
  - A well-known and understood reduced-dimension technique
  - Performance $\Rightarrow$ JDO performance when <u>all</u> Doppler DOFs used
  - Covariance matrices are reasonably sized: <u>trainable</u> & <u>invertible</u>
  - In SAR imagery, adaptive processing of crossrange bins is equivalent to applying GMTI or DBS Doppler bins to EFA
    - Using only one crossrange/Doppler bin is factored time-space algorithm (FTS) = EFA with just one Doppler DOF
    - Increasing Doppler DOFs increases performance

Outline

- MRP CONOPS
  - DBS as the common ancestor of SAR and GMTI
  - Specialized mode with limited coverage
  - Post-Doppler STAP model
- **Long Dwell Processing**
- Benefits
- Target Motion Effects
- Summary

Multi-Resolution Timeline

<u>BASELINE MODE</u>

Short-Dwell GMTI	Short-Dwell GMTI

0	75ms	150ms
0	3x32-48	3x32-48

<u>MULTI-RESOLUTION MODE</u>

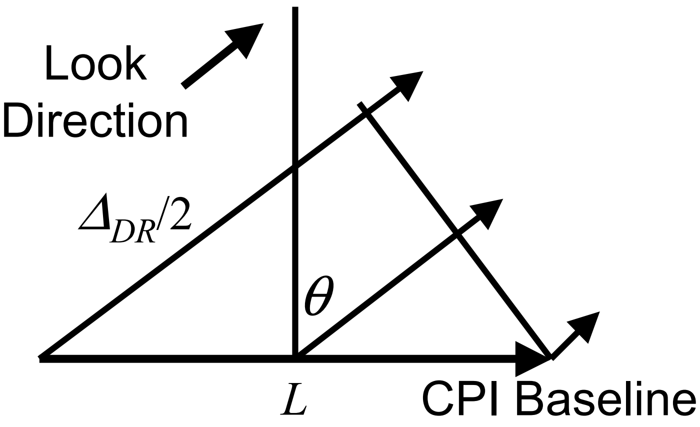
Short-Dwell GMTI	MoComp To Line	MoComp To Point	SAR Imaging (PFA)

0	0.07s	0.25s	0.5s	1-2 s
0	128	512	1024	2,000-4,000

- Dwell time limited by off-boresight range drift
  - Assume a side-looking array
  - MRP area of interest requires scanning away from broadside
  - As dwell time increases, targets and clutter begin to walk through range bins

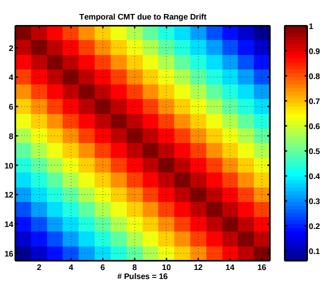
Range Drift Along Velocity Vector

- Limit walk to half-bin, $\Delta_{DR}/2 \Rightarrow$
- Serious problem for discretes
  - Drift through range bins causes AM on signal history
  - Discrete under-nulled, causing SINR loss and false alarms
- Also a problem for targets
  - Even very slowly moving targets drift through range bins
  - Steering vector mismatch $\Rightarrow$ SINR loss
- Effects even distributed clutter
  - AM $\Rightarrow$ temporal CMT (like ICM)

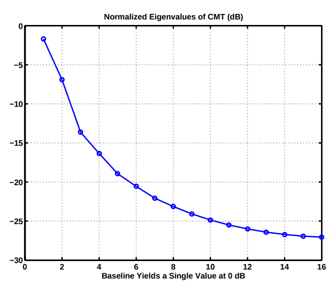


- Range Drift
- Range bin limit: $\boxed{L \le \dfrac{\Delta_{DR}}{2\sin\theta}}$
- Example
  - Δ_{DR} = 15 m, θ = 60°
  - $L \le$ 8.6 m
  - Ownship speed of 125 m/s provides 0.07 s CPI
  - PRF of 2,000 Hz yields 138 pulses

CMT

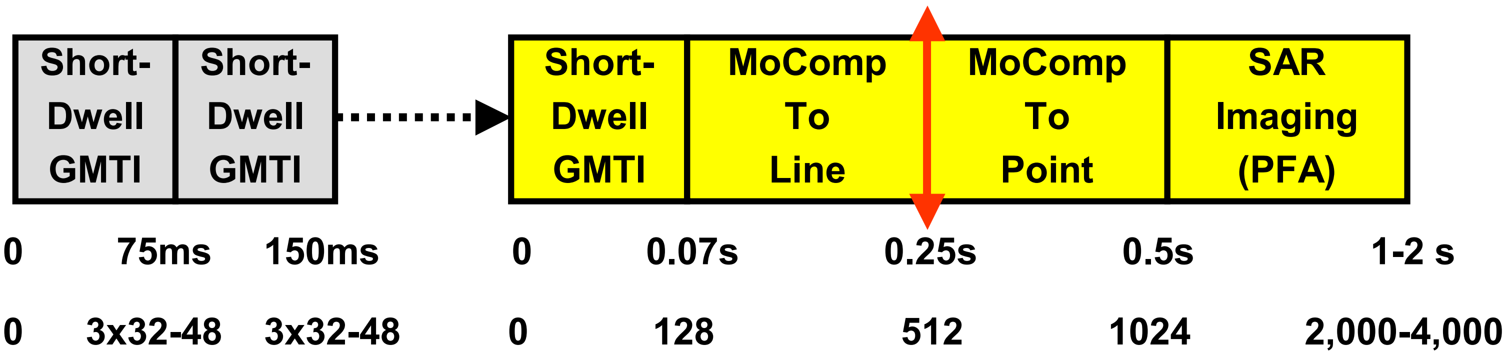


Eigen Values



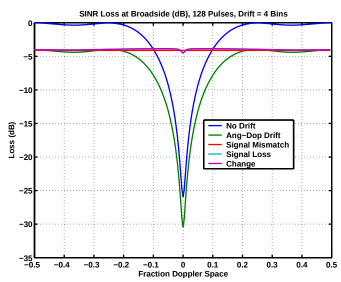
Multi-Resolution Timeline

BASELINE MODE | MULTI-RESOLUTION MODE



- Clutter angle-Doppler drift
  - Drift is along clutter ridge
  - No effect on clutter eigen spectrum
  - A problem for targets: SINR loss due to target mismatch

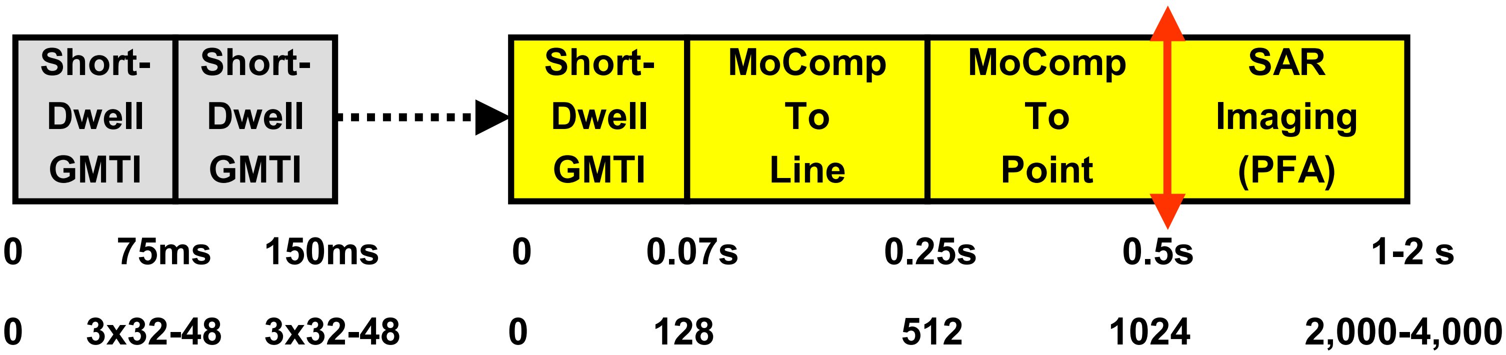
Additional loss due almost entirely to mismatch between target and steering vector



- Some range drift also occurs
  - Clutter (including discretes) and targets experience range drift through bins
  - Significant at high range resolutions and large spotlight area (mainbeam angle is wide)

Multi-Resolution Timeline

BASELINE MODE MULTI-RESOLUTION MODE



- Clutter motion through resolution cells (MTRC)
  - A finite integration angle is required to achieve crossrange resolution
  - Scatterers walk through range and Doppler (crossrange) resolution cells over the course of the dwell, blurring their responses
- Some angle drift also occurs
- Again, not a problem with homogeneous clutter, but
  - Discretes: Drift smears returns for discretes away from scene center
  - Targets: Even very slowly moving targets smear in angle and Doppler

Multi-Resolution Timeline

BASELINE MODE

Short-Dwell GMTI	Short-Dwell GMTI

0	75ms	150ms
0	3x32-48	3x32-48
0	3x240m	3x240m

MULTI-RESOLUTION MODE

Short-Dwell GMTI	MoComp To Line	MoComp To Point	SAR Imaging (PFA)

0	0.07s	0.25s	0.5s	1-2 s
0	128	512	1024	2,000-4,000
0	85m	24m	12m	6m-3m

- Limits on approximations
  - Drift along clutter ridge is not constant rate, a function of angle
  - Range drift compensations work only at scene center
  - Some residual angle drift
- Near-field effects can occur
  - Large scene sizes and large integration angles
  - Spatially-variant defocusing and geometric distortion are the drawbacks

> • Need to substitute MoComp operations and PFA imaging with high-fidelity SAR focusing: back projection or ω–k algorithm

Outline

- MRP CONOPS
- Long Dwell Processing
  - MoComp to a line
  - MoComp to a point
  - SAR imaging (PFA)
- **Benefits**
- Target Motion Effects
- Summary

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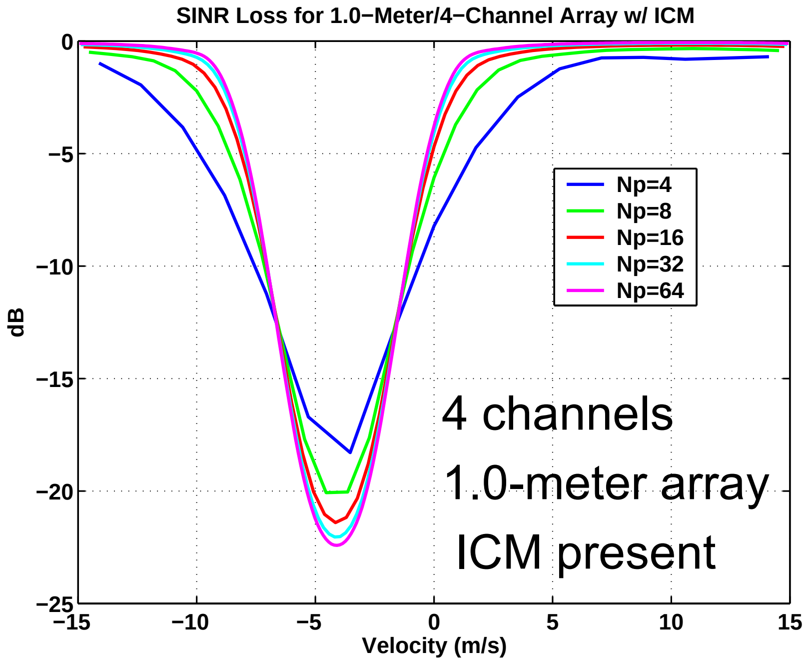
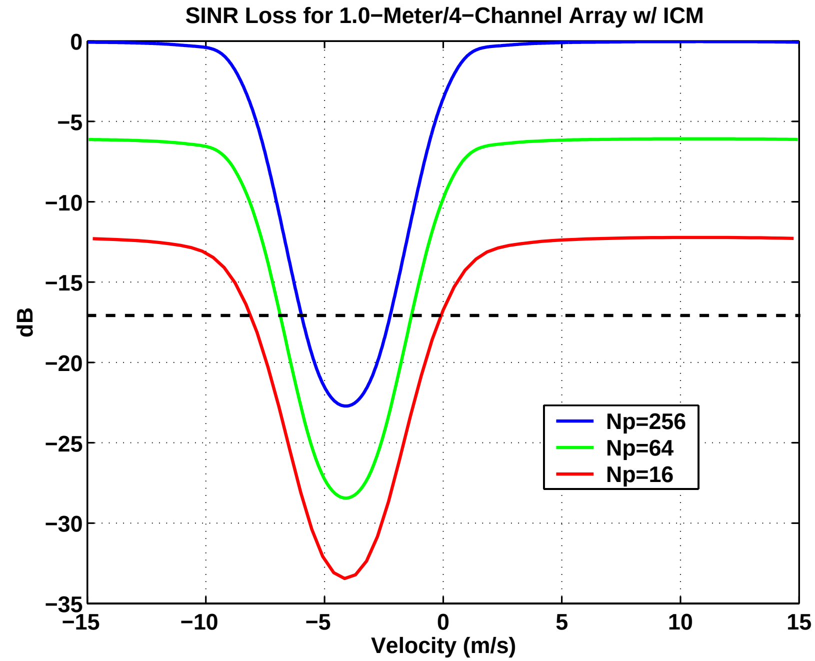
Integration Gain



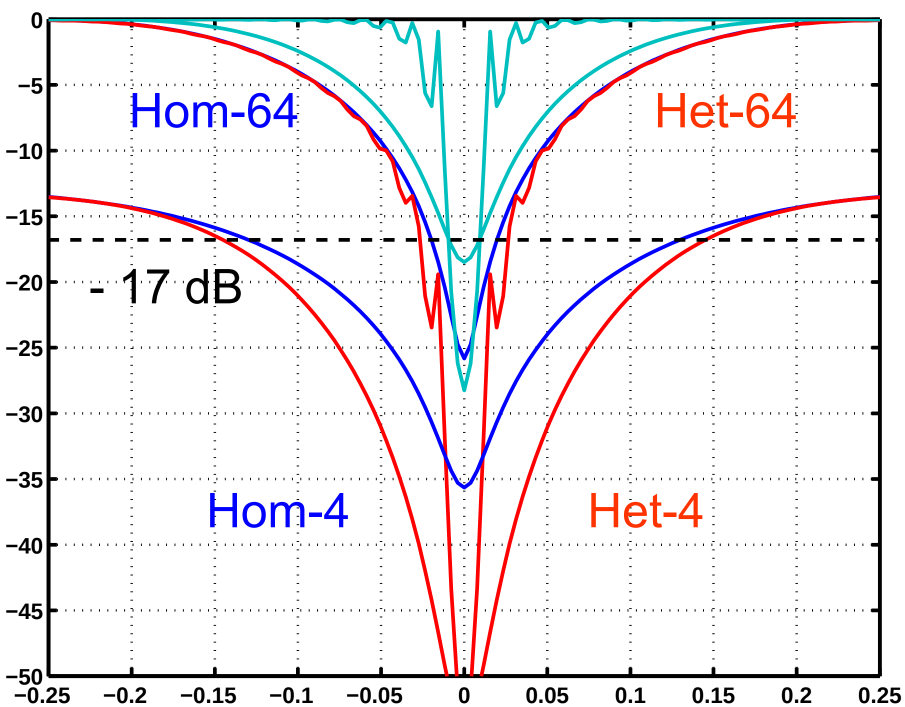


- SINR-loss is relative in figure at left; suggests negligible performance gain with increasing number of pulses beyond 16
- <u>However</u>, figure at right uses SINR normalized to 256 pulses; dashed line at –17 dB is the –5 dB MDV limit for 16-pulses
- Using the dashed line as a reference, **MDV decreases with increasing pulse number via coherent integration of target against thermal noise**

Discrete Effects Using Normalized SINR

- Normalized SINR
  - 0 dB for 64 pulses
  - Dashed line at -17 dB denotes the -5 dB level for the 4-pulse case
- Using the dashed line:
  - Small MDV impact (red versus blue) for both 4 and 64 pulses
  - Fractional change in MDV is substantial for the 64-pulse case

Het-Hom Difference for 4 and 64 Pulses



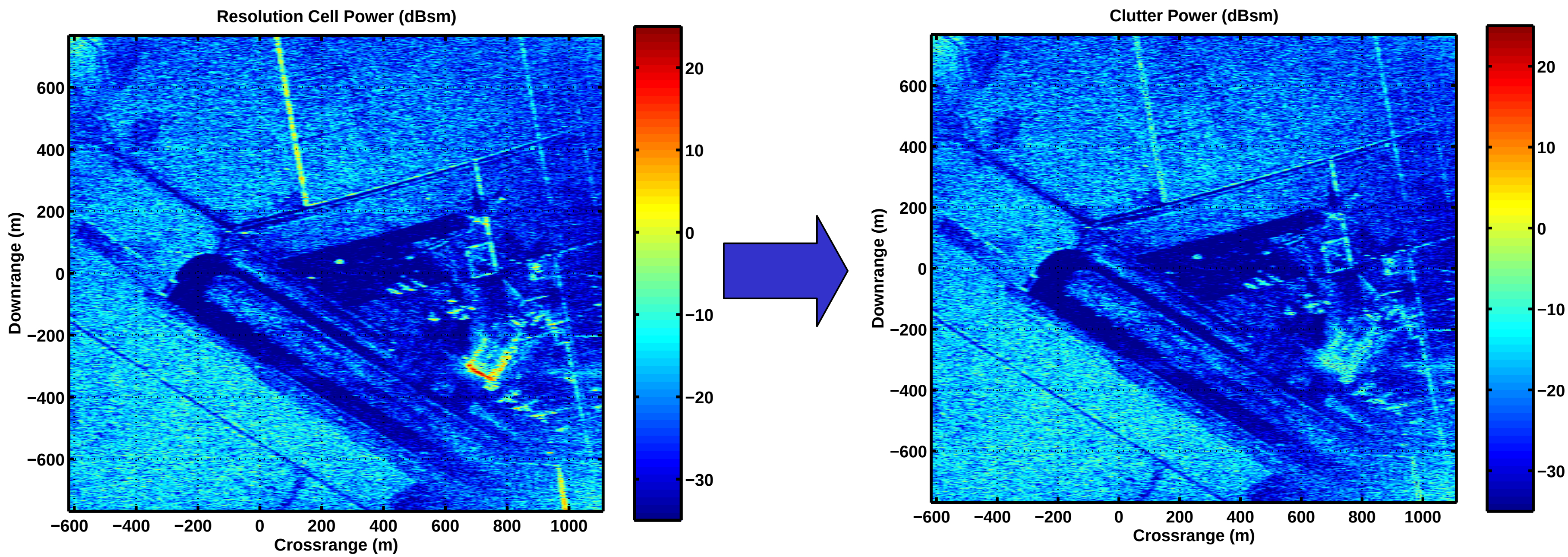
Discretes can cause large *percent* increase MDV at fine resolutions

Discrete Mitigation Options

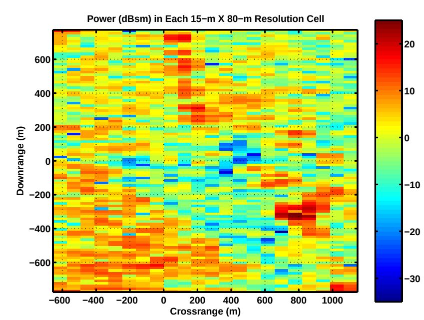
1. Include CUT in training data
2. Remove discretes from data

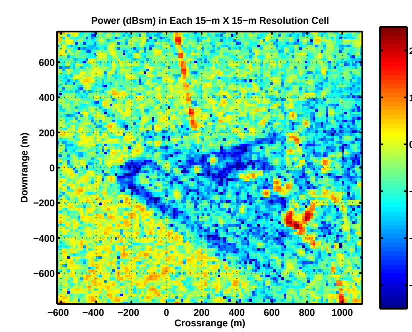
Discrete Suppression

- Estimate and remove discretes using the CLEAN algorithm:



- An option at fine resolutions only!
  - Difficult to identify discretes at coarse resolutions ⇒

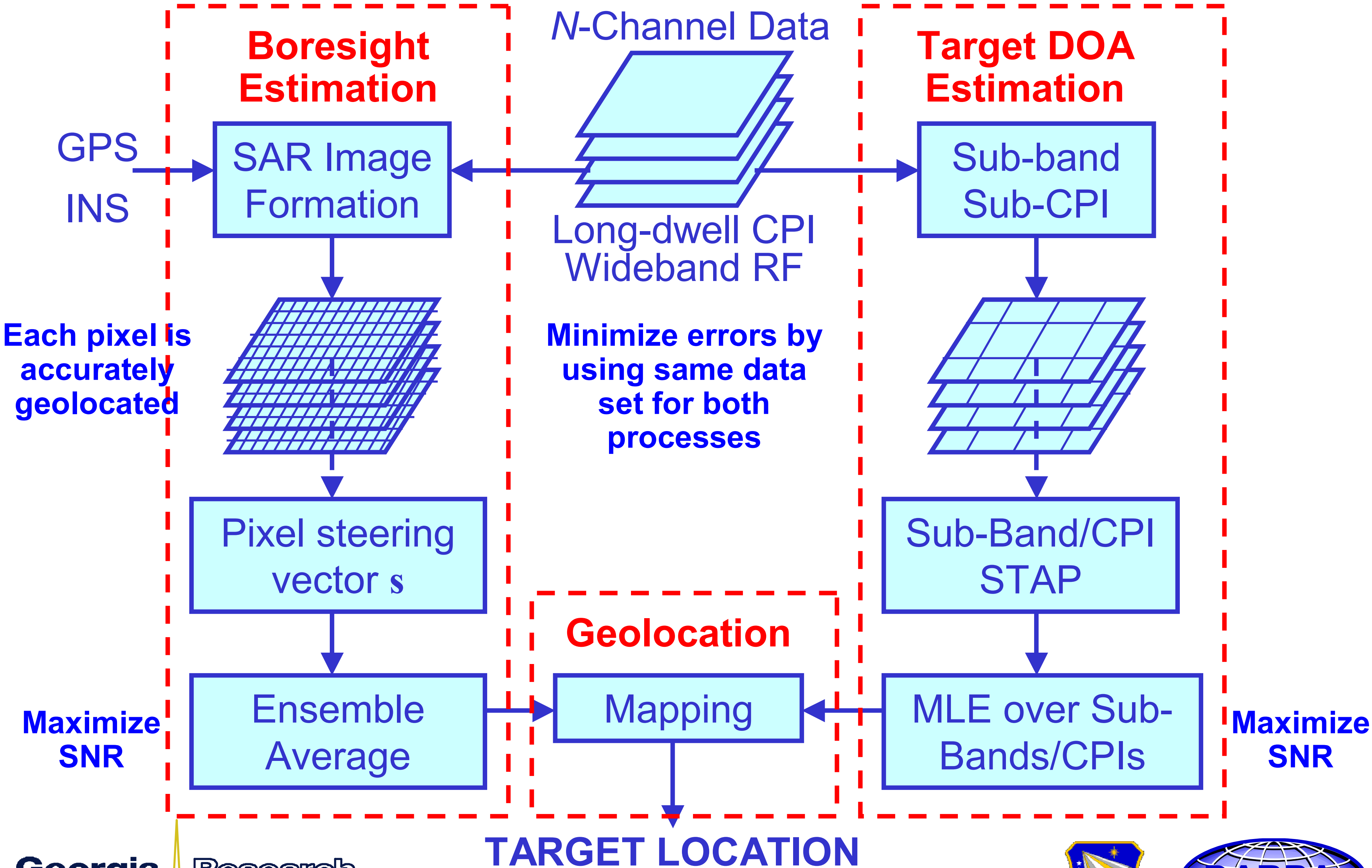




Array Error Issues

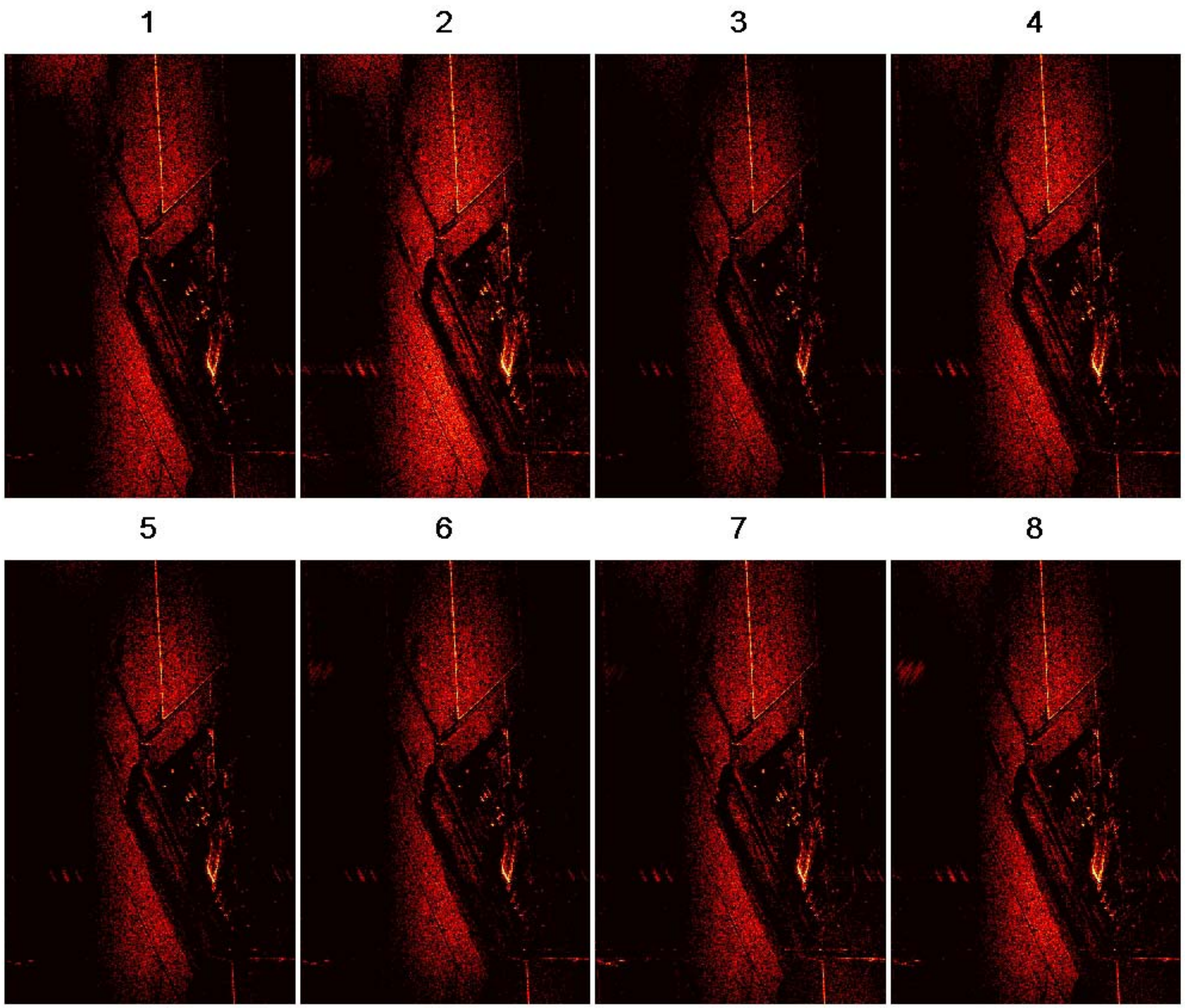
- Array errors have been shown to limit the benefit of some knowledge-aided techniques
  - Colored Loading (CL) of covariance estimate
  - Pre-Whitening (PW) of data cube
- **SAD** addresses estimation of array errors
  - SGMTL AESA Demonstration Program
  - AFRL sponsored, GTRI lead, Raytheon subcontractor
  - Geolocation of slow-moving ground targets
- SAD addresses estimation of array errors
  - Raytheon performing this subtask
  - See Association of Old Crows (AOC) presentation
    - March 2003
    - Jeff Hoffner, Trung Nguyen, et al

SAD Geolocation Procedure



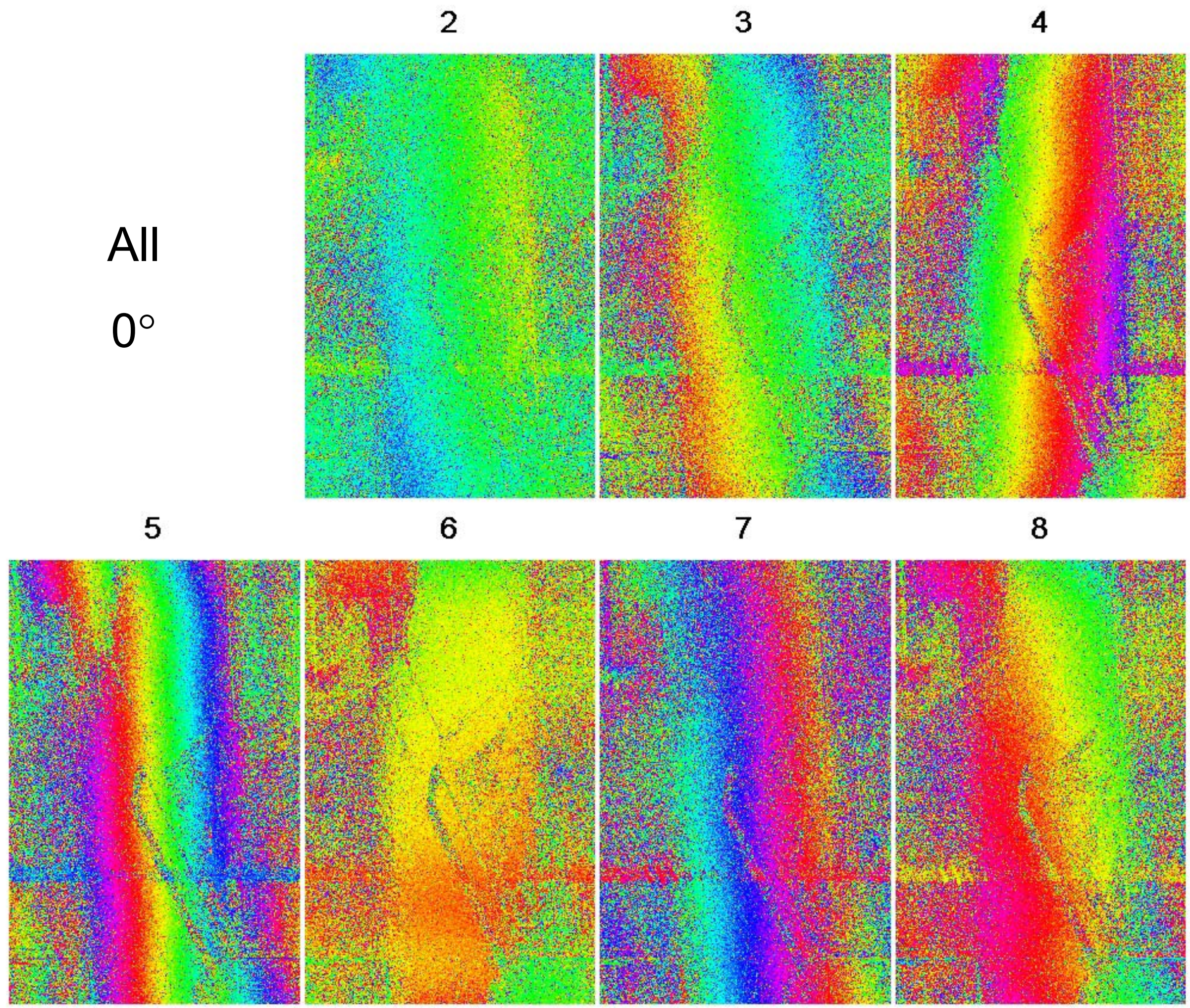
APTI 8-Channel DBS Images

- Array calibration example using Raytheon APTI 8-channel X-band radar
- “SAR” image formed in each channel
- SAR images are geolocated; this allows pixel # to be mapped to Lat and Long



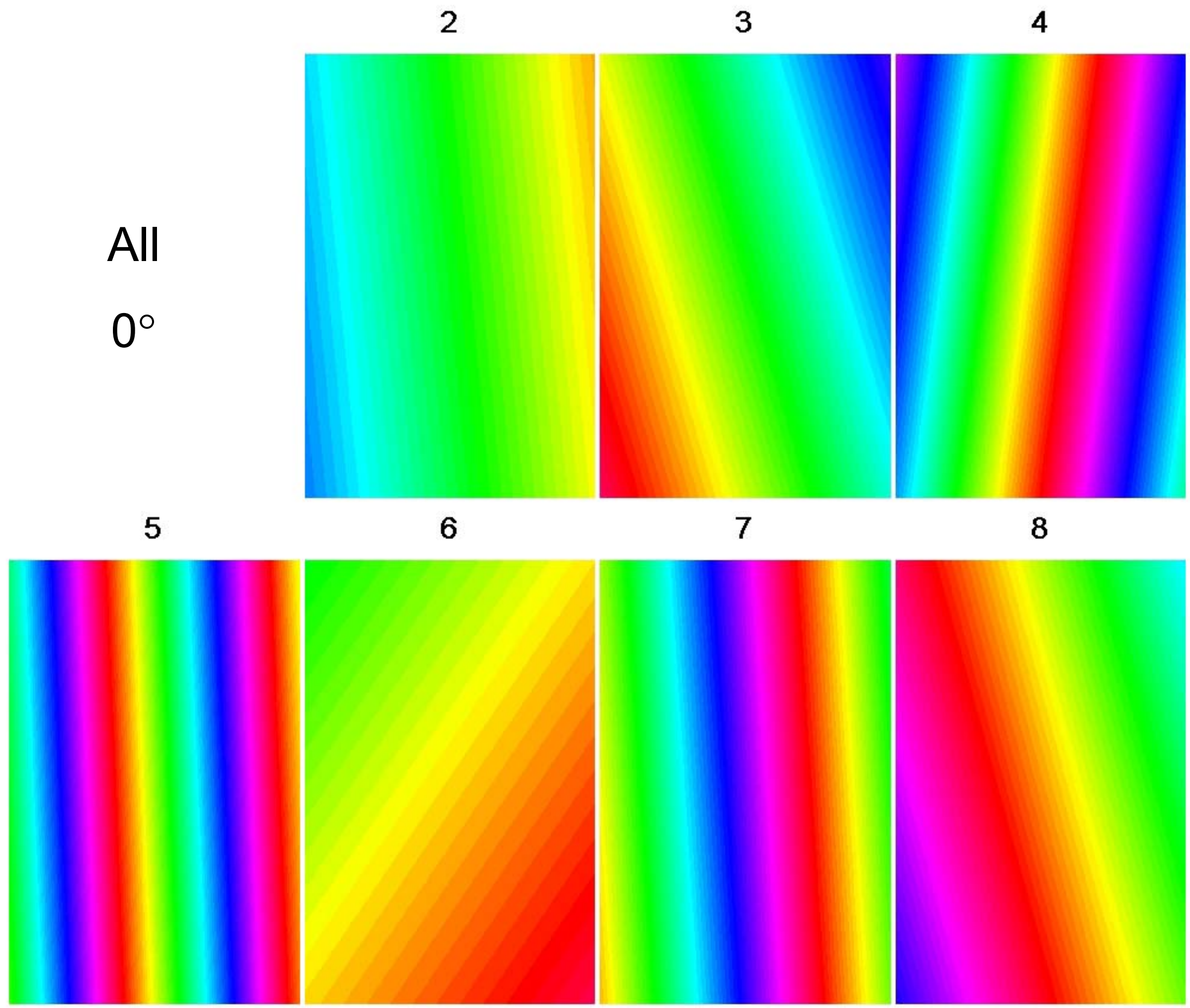
APTI 8-Channel Phase Differences

- Pixel-by-pixel phase differences between channels (relative to #1)
- For a given pixel, the 7 phases are an estimate of the array steering vector to that pixel's Lat-Long
- Desire averaging to increase SNR and accuracy of array response estimates, and eliminate low-power regions



1st-Order Phase Function Fits to APTI

- Apply 1st-order estimator: mean phase, vertical slope, and horizontal slope
- Find Weighted (by pixel cross-power) Least Squares (WLS) solution for each channel
- This approach is more sophisticated than moving window averaging, and accounts for low-power areas



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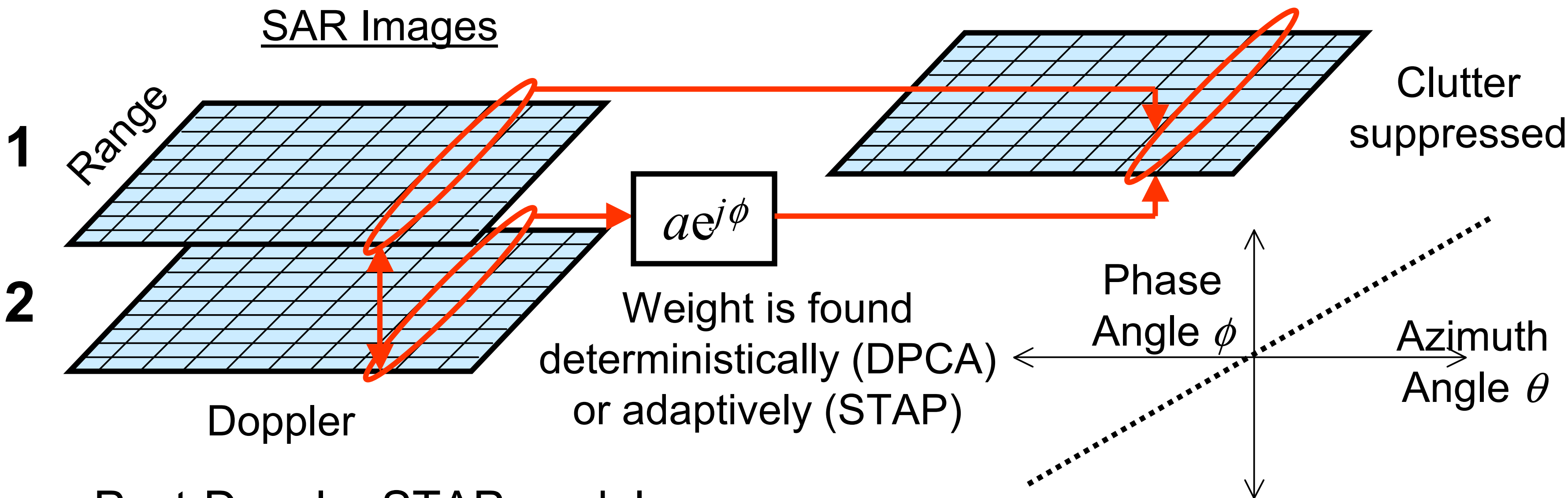
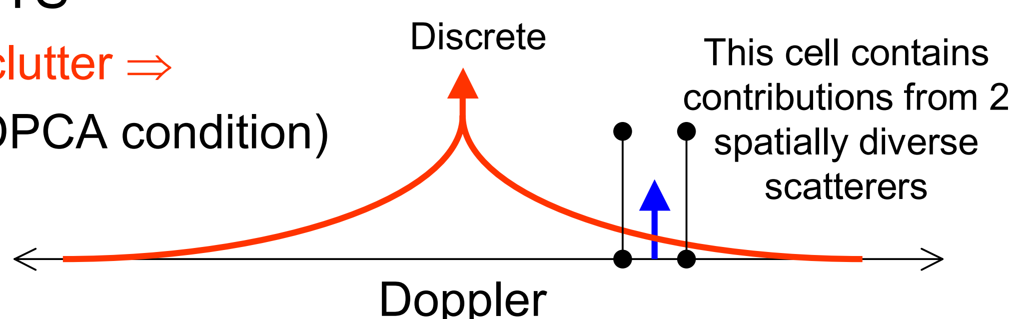
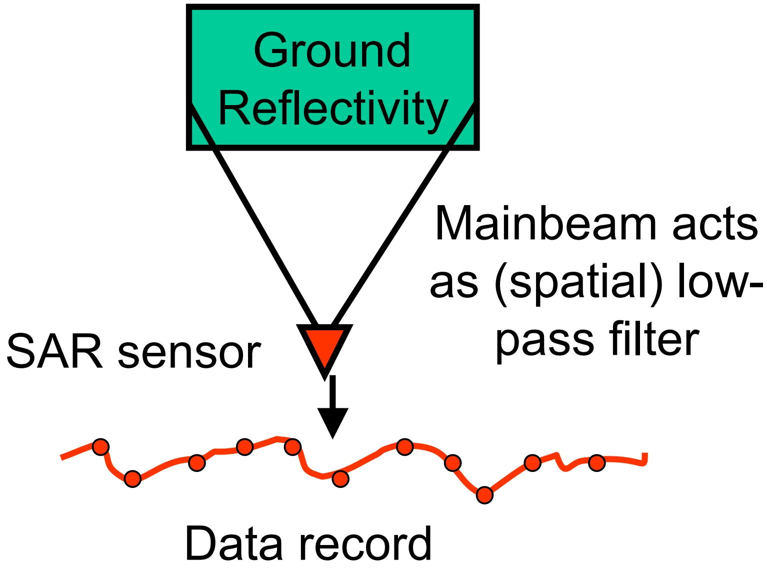
Post-Doppler Clutter Cancellation



- Post-Doppler STAP model
  - Spatial cancellation as a function of crossrange/Doppler
  - EFA preferred over FTS (single Doppler DOF EFA)
- Performance limitations of FTS
  - 1. Sidelobes from nearby clutter $\Rightarrow$
  - 2. Backlobe returns (non-DPCA condition)
  - 3. ICM
  - 4. Registration errors



SAR Clutter Cancellation via Resampling

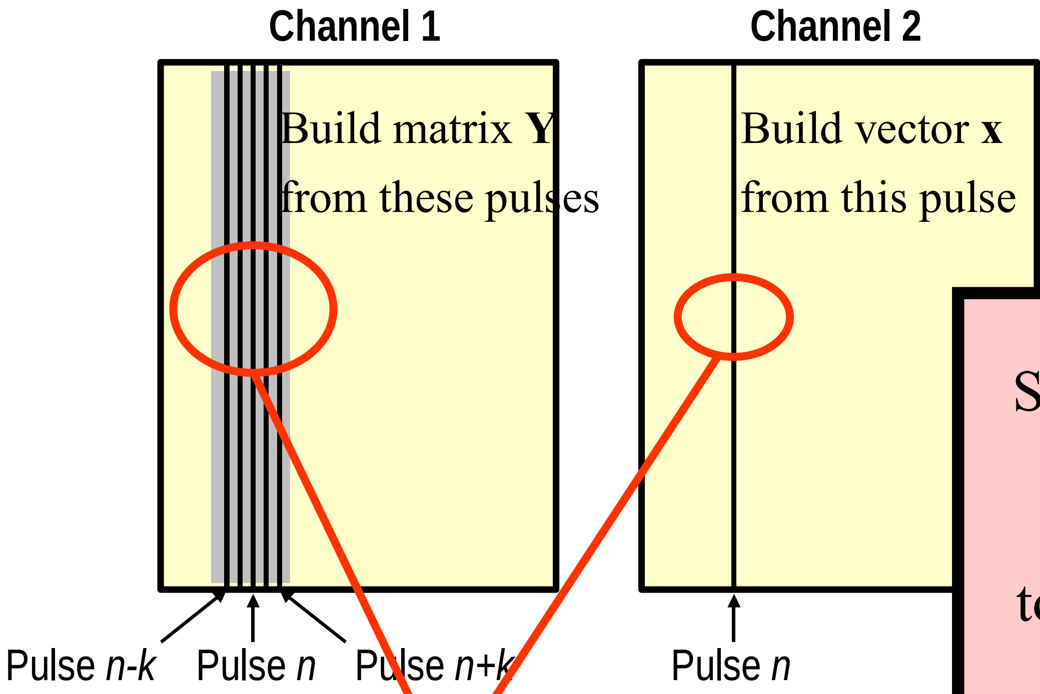


- Complex baseband output for single range bin or frequency
  - Nyquist sampling is $\lambda/2$
  - Antenna gain pattern acts as a low pass filter; Nyquist achieved with coarser sampling
- Nyquist is achieved in SAR (for the mainbeam) if clutter is unambiguous in Doppler

- When Nyquist is achieved, we can resample data record <u>without loss or error</u>
- Options
  - 1. Use SAR image former to effect resampling
  - 2. Resample data in each channel relative to a reference channel
    - Implementation can be deterministic or adaptive

“Channel Equalization Technique”

Taken from ALPHATECH KASSPER QPR, Sept. 23, 2002



Adapt filter by solving new optimization problem at each pulse location

Find linear combination of Channel 1 pulses that yields best approximation of corresponding Channel 2 pulse

Solve

$$\min_{\mathbf{h}} \left\| \mathbf{Y}\mathbf{h} - \mathbf{x} \right\|^2$$

to get optimal data-derived filter

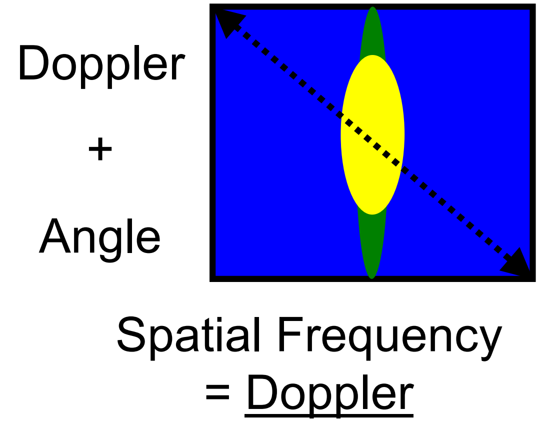
$$\mathbf{h}_o = \left(\mathbf{Y}^\dagger \mathbf{Y}\right)^{-1} \mathbf{Y}^\dagger \mathbf{x}$$

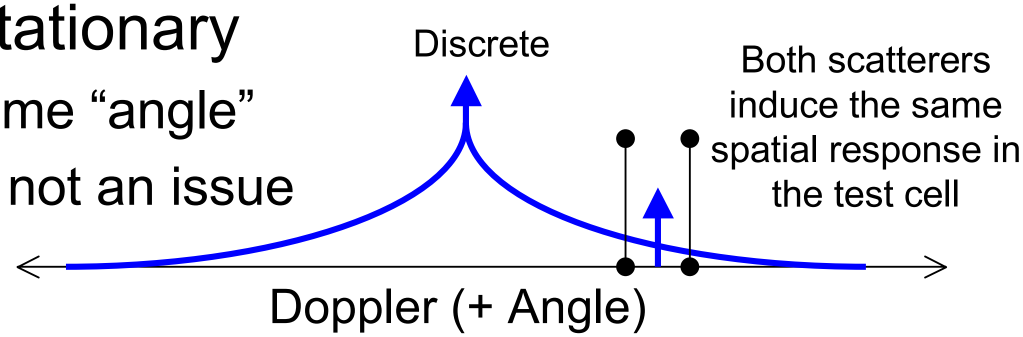
and, in turn, the new pseudo-pulse

$$\hat{\mathbf{x}} = \mathbf{Y}\mathbf{h}_o$$

Benefits of Resampling

- Clutter DOFs are reduced
  - Example: From $M+N-1$ to M
    - No ICM, start at DPCA condition
  - Training requirements decreased
  - Training not limited to range, but can be performed over Doppler as well
- Spatial responses are stationary
  - All clutter now has the same “angle”
  - Sidelobes from discretes not an issue





Up-front adaptive interpolation of the raw data, or deterministic resampling in range-Doppler by the SAR image former, eases the burden on the subsequent STAP stage

Outline

- MRP CONOPS
- Long Dwell Processing
- Benefits
  - Integration gain
  - Discrete suppression
  - Array calibration
  - Data resampling
  - Increased samples for localized training
- **Target Motion Effects**
- Summary

Moving Target Effects

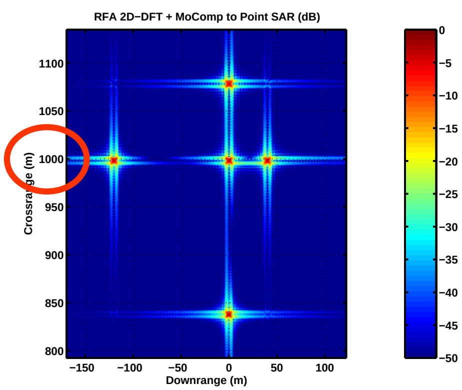
- Bad news…
  - Moving target has range migration and Doppler drift
  - Leads to smearing/blurring of target in the SAR image
  - Reduces SINR in any given test cell
- Good news…
  - SAR imager compensates for range migration
  - Linear motion along LOS fully accounted for
  - Only along-track motion remains
  - Not doing imaging, so higher-order effects can be neglected

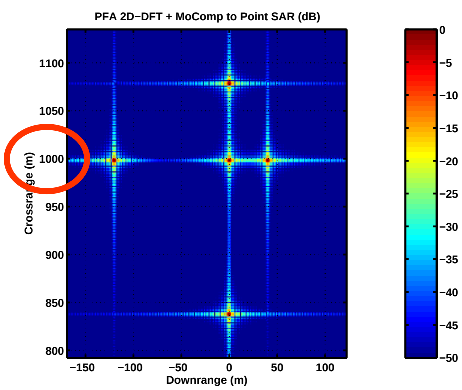
Array of targets at (0,0) move 5.25 m cross-track during CPI.

Array offset to (0,1000)

Range and Doppler blurring also results.

(3-meter resolution)





When MoComp-to-a-point is followed by PFA, movers are focused in range and Doppler

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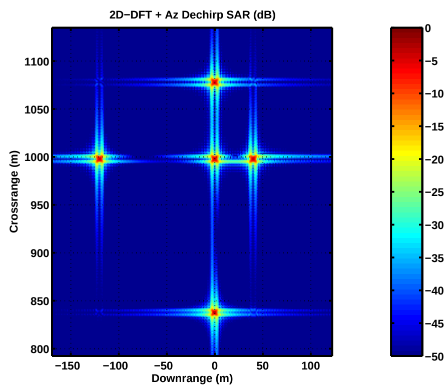
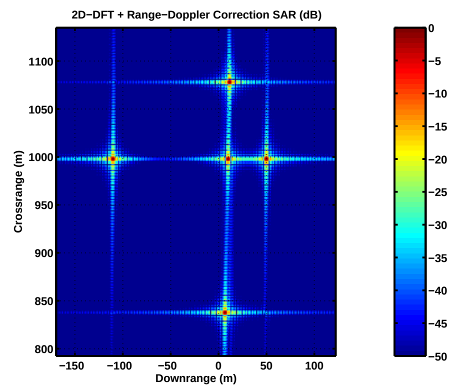
SAR Image Formers and Target Motion

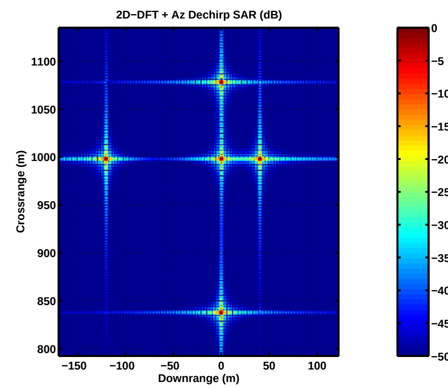
Same movers after
Az Dechirp & FFT



Range-Doppler
Processing



Keystone
Reformatting



→ MoComp to Point → PFA →

→ Range-Doppler (RD) Processing → Az Dechirp →

→ Keystone Formatting → Az Dechirp →

→ ω-k (RMA) →

→ Back Projection →

These stages account for target cross-track motion

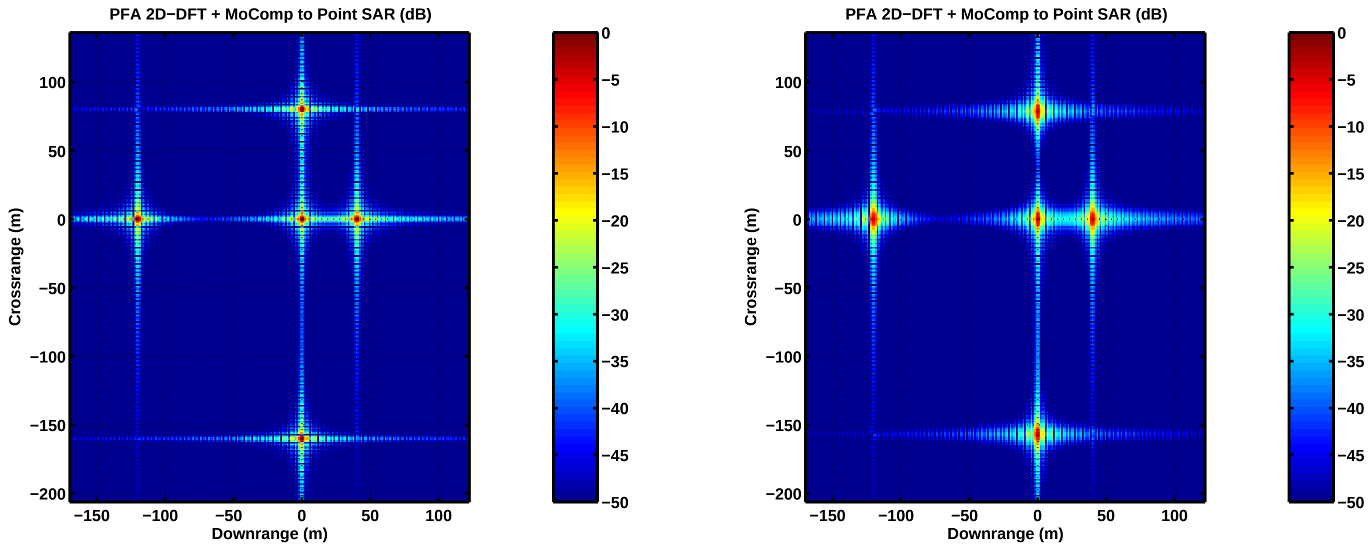
Along-Track Motion Remains

Array of targets at (0,0):

1. Are stationary, and
2. Move 5.25 m along-track during CPI.

PFA processing

(3-meter resolution)



- SAR image formers cannot compensate for along-track motion of targets
- Along track motion is manifested as slow-time QPE (chirp)
  - Consequent blurring of target return in crossrange (Doppler)
  - Remove via (1) slow-time dechirp, or (2) crossrange FIR filtering
- Negligible until motion over CPI $\approx \Delta_{CR}$
  - This occurs at 1-2s CPI, 6-m to 3-m resolution

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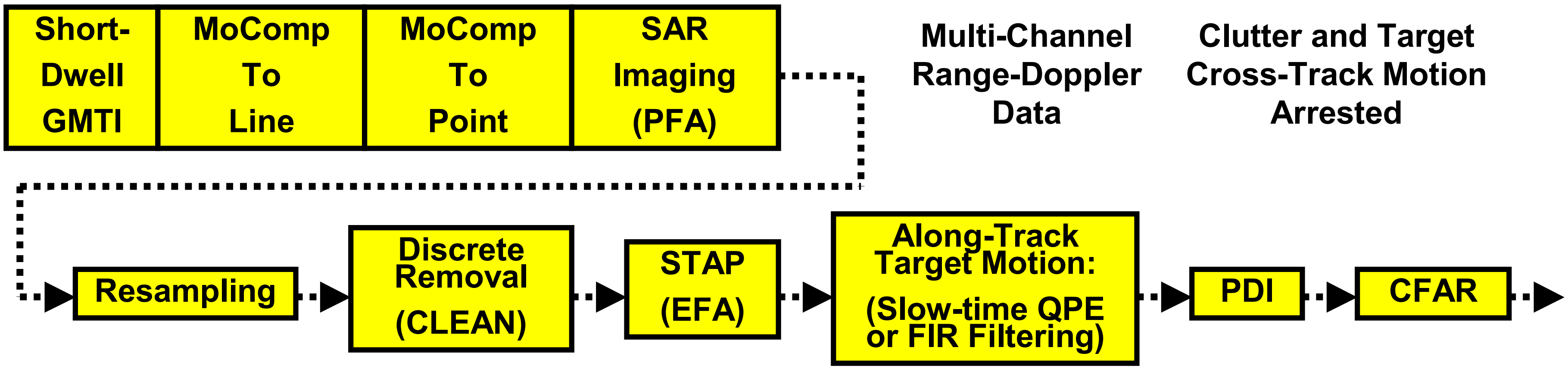
Outline

- MRP CONOPS
- Long Dwell Processing
- Benefits
- Target Motion Effects
  - SAR image former accounts for across-track motion
  - Along-track motion results in crossrange defocusing
  - Compensate with slow-time dechirp or FIR filtering
- Summary

MRP Summary



- Benefits
  - Integration gain
  - Discrete suppression
  - Array calibration
  - Rank reduction (resampling)
  - Samples for localized training
- Challenges
  - Target “decorrelation”
  - Area coverage
    - Bandwidth considerations
    - DAR, spoiled TX beam
    - Feedback?!

This is not a SAR program!!!

SAR-like motion compensation, focusing, and image formation used to make long-dwell STAP/GMTI viable

Back-Up Slides

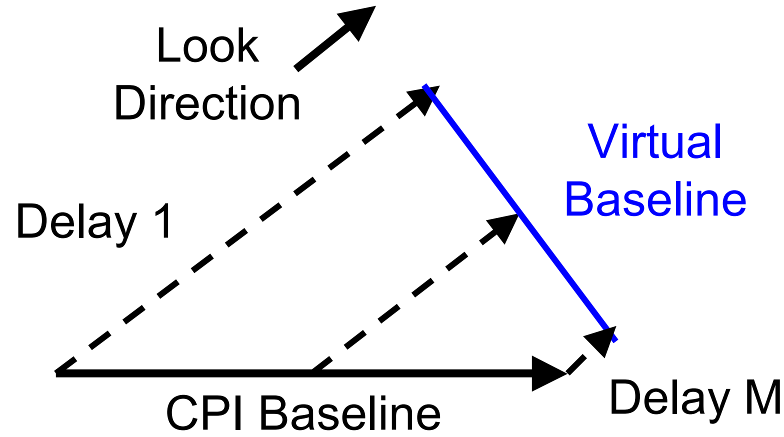
Bandwidth Issues

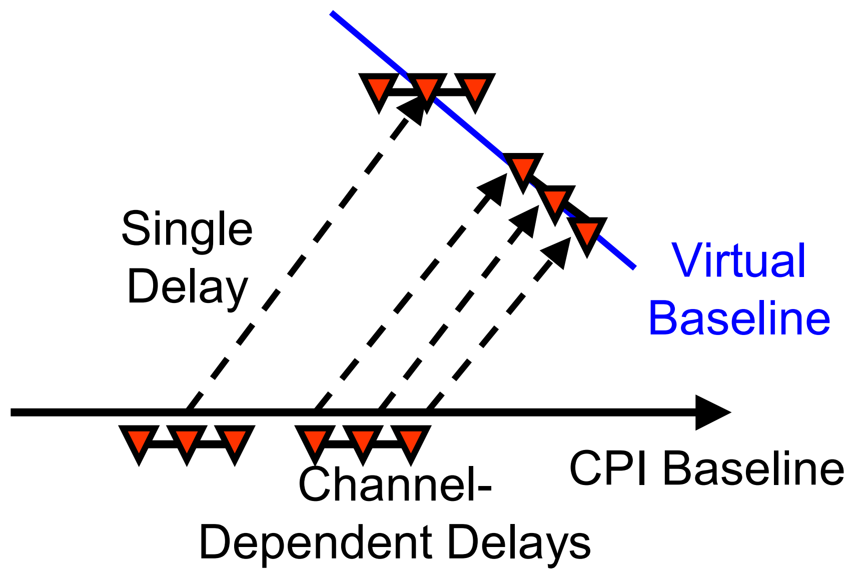
Two Different MRP Modes Depending on Operating Bandwidth

- Narrowband
  - Convolution (matched filtering)
  - 5-20 MHz bandwidth
  - 30 to 7.5 m resolution
  - 25 km to 50 km swath depth
  - Summary of advantages
    - Deep swath coverage
    - Dwells can be long before motion compensation becomes an issue
- Wideband
  - "Stretch" processing
  - 50 MHz to 1 GHz bandwidth
  - 3 to 0.15 m resolution
  - 3 km to 150 m swath depth
  - Summary of advantages
    - High downrange resolution
    - Abundance of information (due to fine range bins) permits highly localized processing

MoComp to Look Direction

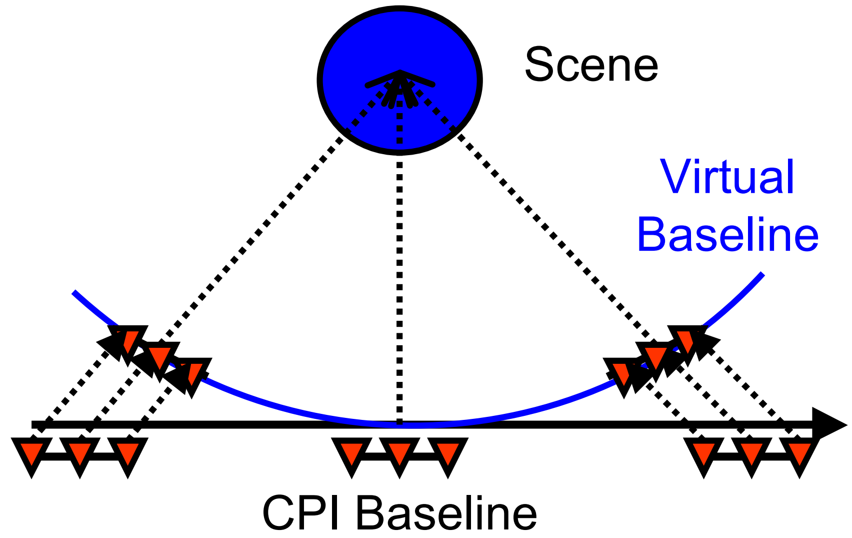
- Progressively delay data records on successive pulses to effect a virtual baseline normal to the look direction
- Delays implemented via linear phase multiplication in the frequency domain
- “Virtual crab” dilemma
  - Applying the same shift to all spatial channels results in effective crab along virtual baseline
  - Different delays for each channel serves to eliminate crab (phase centers must be recalculated so that proper steering vectors are generated)

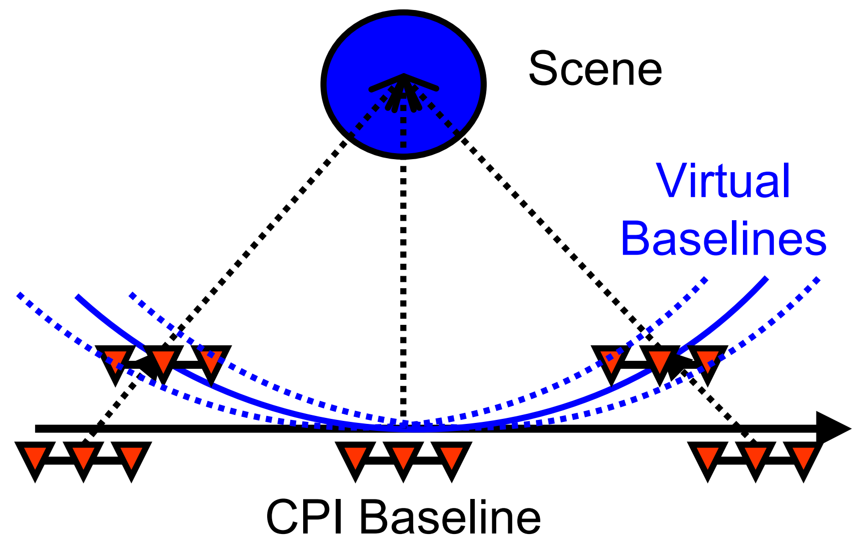




MoComp to Scene Center

- Progressively delay data records on successive pulses to effect a circular baseline about scene center
- Angle, Doppler, and range walk are all removed
  - For limited scene size
- Viable approximations
  - <u>Narrowband</u>: Replace delays with phase modulation ("azimuth dechirp" in SAR parlance)
  - <u>Small array</u>: Neglect angle drift, apply same delay to each spatial channel ⇒





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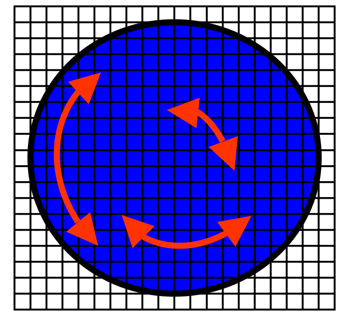
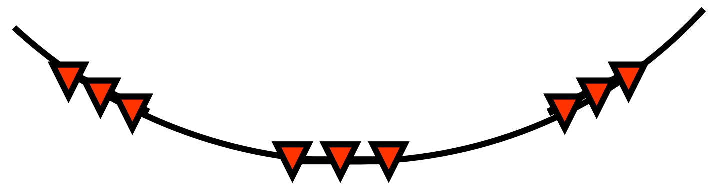
Motion Through Resolution Cells (MTRC)

- MTRC
  - Occurs at fine resolutions and large scene sizes (and low frequencies)
  - Causes downrange and crossrange blurring of scatterers
- Polar Formatting Algorithm (PFA)
  - Compensates for MTRC, range and Doppler walk eliminated
  - Widely used and mature technique; implementation is straightforward
  - Apply to each spatial channel data record

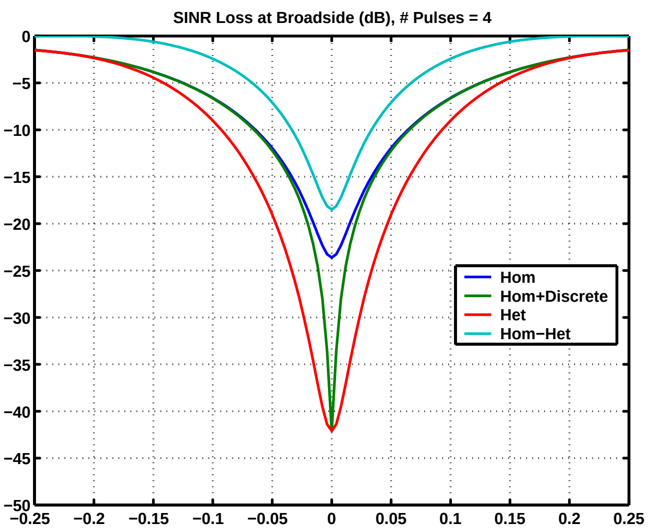


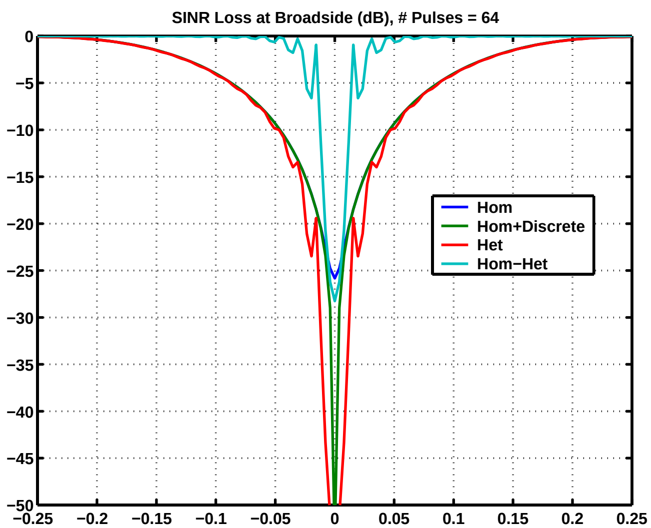


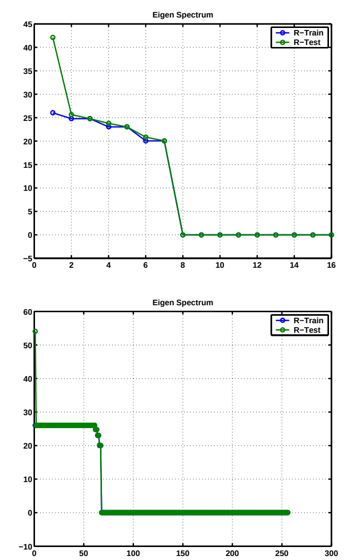
- Motion through resolution cells
- Scene size limit: $D_{Scene} \le \frac{4\Delta_{DR}\Delta_{CR}}{\lambda}$
- Example
  - Δ_{DR} = 1.5 m, λ = 0.03 m, D_{Scene} = 2.0 km
  - $\Delta_{CR} \ge$ 10 m $\Rightarrow L \le$ 75 m (R = 50 km)
  - Ownship speed of 125 m/s provides 0.6 s CPI
  - PRF of 2,000 Hz yields 1,200 pulses

Discrete Effects

- Are discretes a problem at coarse or fine resolutions?
  - Examine SINR of single strong discrete in homogeneous clutter
  - Training does NOT include discrete
  - Number of pulses = 4 and 64 (12 dB difference)
- At first, discretes appear worse at <u>coarse</u> resolutions
  - Significant SINR loss over large fraction of Doppler
  - Some MDV loss at moderate SINR-loss levels







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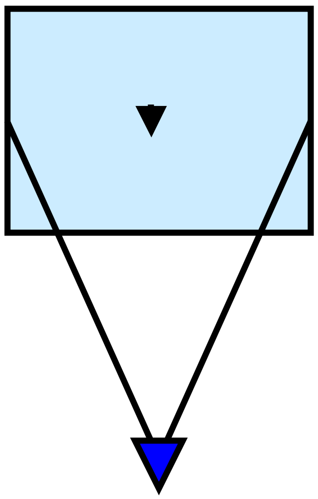
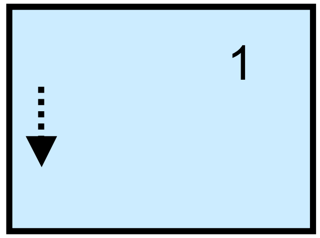
Additional Data for Localized Training

- At moderate resolutions, EFA automatically provides localized training
  - A “freebie” for fighting clutter heterogeneity
- At higher resolutions
  - Resolution cell should be matched to target dimensions
- Example
  - Targets are 7.5 meters by 7.5 meters
    - 20 MHz bandwidth
    - 0.8-second CPI
  - Wideband and long-dwell operation
    - 200 MHz “stretch” BW yields 0.75-meter downrange resolution
    - 4-second CPI yields 1.5-meter crossrange resolution
  - Target consists of 50 resolution cells
- Impact on processing
  - 50:1 PDI required on final range-Doppler output from EFA
  - For fixed training area (in meters), 50x more training samples are available

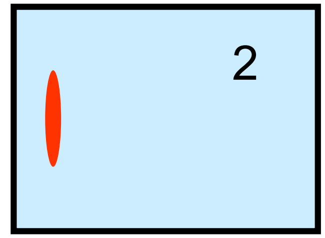
SAR Imagers Compensate Target LOS Motion



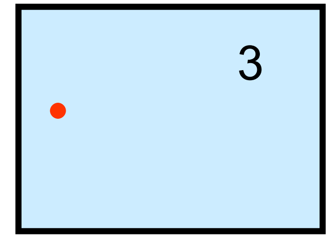
SAR imaging with moving target at broadside, moving directly towards the radar



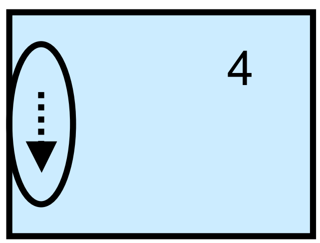
Target motion causes (1) Doppler, displacement in crossrange, and (2) smearing in range



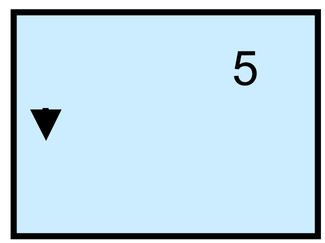
SAR imager expects stationary returns at that location to be smeared (due to range walk)



The imager compensates for motion, so scatterer is focused



The same compensation is applied to the smeared moving target



The result is that the smeared target is focused in range

Key concept:

The Doppler of the mover is consistent with its downrange motion, and the SAR imager uses Doppler to compensate for range walk.

Along-Track Motion Compensation

- Using post-Doppler STAP (EFA) weight $\mathbf{w}$, calculate output for m^{th} Doppler filter at k^{th} range bin for n^{th} steered direction: $y(m;k,n) = \mathbf{w}(m;k,n)^H \mathbf{x}(m;k)$
  - $\mathbf{w}$ must be constrained to gain = 1 in target direction
- Form vector of M Doppler outputs $\mathbf{y}(k,n)$
- Compensate by one of two methods
  - Removal of QPE (dechirp) in slow-time
    - $\mathbf{y'} = \mathbf{W}^H[\mathbf{diag}(QPE^*)]\mathbf{W}\mathbf{y}$
  - Low-order FIR filtering in Doppler $\Rightarrow$
    - $y'(m) = y(m) *^m * h(m)$